DRA.

GARRETT 21-4766

EXECUTIVE SUMMARY AEROTHERMAL MODELING PROGRAM PHASE I

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Garrett Turbine Engine Company
A Division of The Garrett Corporation

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Prepared for

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Project Manager: Dr. J. D. Holdeman
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16. Abstract

The main objective of the NASA Aerothermal Modeling Program, Phase I was to assess current submodels used in the Garrett combustor analytical models that have been successfully used in designing advanced technology combustors. Another objective of the study was to make specific recommendations for further improvement of model accuracy for combustor design purposes.

Based upon an exhaustive literature survey, a number of test cases were selected to assess accuracy of submodels of turbulence, turbulence/chemistry interaction, spray combustion, and dilution jet mixing processes within a confined cross-stream. These test cases included simple flows and complex flows with and without swirl. Nonrecirculating and recirculating, and nonreactive and reactive flows were investigated.

Based on this investigation and prior work at GTEC, it was concluded that the current models give qualitative trends for the recirculating secondary flows (as encountered in a gas turbine combustor primary zone), but the predictions are good for the dilution zone. Further work should include development of advanced numerical schemes and more accurate turbulence/chemistry interaction models. Benchmark quality data should be collected for flows of relevance to modern gas turbine combustors.

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FOREWORD

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NASA AEROTHERMAL MODELING

OBJECTIVE: ASSESS CURRENT COMBUSTOR MODELS AND IDENTIFY MODEL DEFICIENCIES

APPROACH

TASK I
- MODEL DEFINITION
- DATA BASE GENERATION
- BENCHMARK TEST CASES

TASK II
- MODEL EXECUTION
- MODEL ASSESSMENT
- PROGRAM PLAN FOR MODEL IMPROVEMENT

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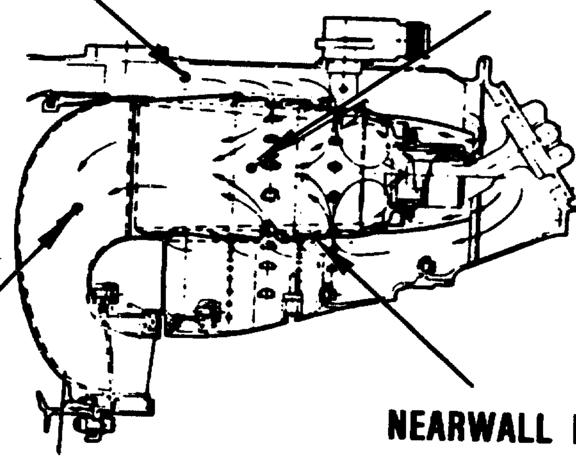
MODULAR APPROACH FORMS THE BASIS OF COMBUSTION ANALYSIS AT GTEC

ANNULUS FLOW MODEL

- PRESSURE DROP
- AIRFLOW DISTRIBUTION
- BOUNDARY CONDITIONS

COMBUSTOR FLOW MODEL

- INTERNAL FLOW FIELD
- TEMPERATURE & F/A DISTRIBUTION



TRANSITION MIXING

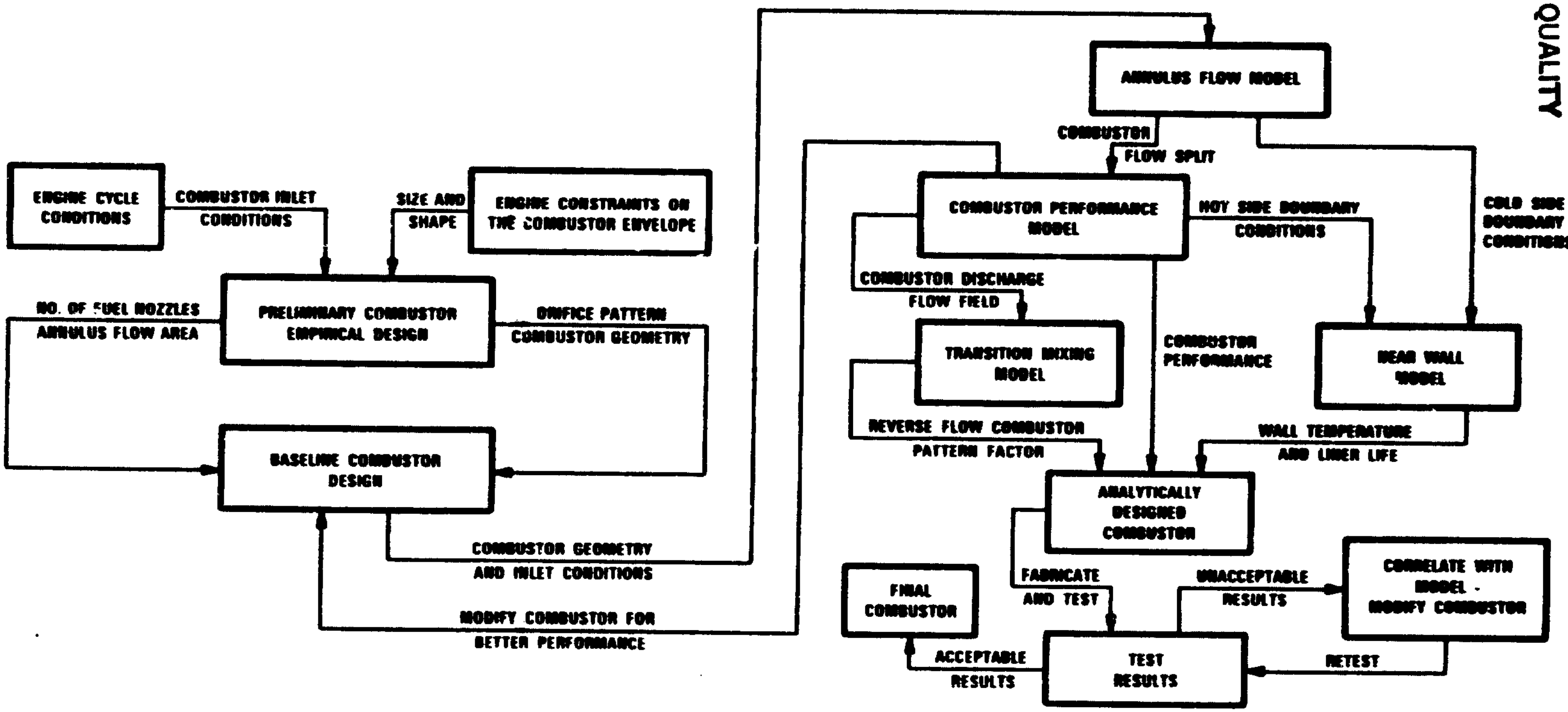
- JET MIXING
- BURNER EXIT TEMPERATURE QUALITY

NEARWALL MODEL

- LINER CONVECTIVE AND RADIATIVE FLUXES
- LINER WALL TEMPERATURE DISTRIBUTION

63-0205-2

EMPIRICAL/ANALYTICAL DESIGN APPROACH HAS BEEN SUCCESSFUL IN SEVERAL COMBUSTOR DESIGNS



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SUBMODELS ARE USED TO DESCRIBE THE FOLLOWING SEVEN COMBUSTION PROCESSES

- TURBULENCE
- SCALAR TRANSPORT
- CHEMICAL KINETICS
- TURBULENCE/CHEMISTRY INTERACTION (GASEOUS COMBUSTION)
- SPRAY EVAPORATION/COMBUSTION
- SOOT FORMATION AND OXIDATION
- RADIATION

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k-ε TURBULENCE MODEL IS WIDELY USED FOR RECIRCULATING FLOWS

- **TRANSPORT EQUATION**

$$(C-D)\phi = S_\phi$$

$$G_K = G_K \text{ (MEAN VELOCITY GRADIENTS)}$$

$$S_k = G_k - \rho\epsilon$$

$$S_\epsilon = (C_1 G_k - C_2 \rho \epsilon)\frac{\epsilon}{k}$$

$$\mu_t = C_D \rho k^2/\epsilon$$

$$\sigma_{eff,\epsilon} = \frac{\kappa^2}{(C_2 - C_1)\, C_D^{1/2}}$$

C_D = 0.09
C_1 = 1.44
C_2 = 1.92
$\sigma_{eff,\,k}$ = 0.9
κ = 0.41

- **WALL FUNCTION ARE USED FOR NEAR-WALL REGIONS**

LOW-REYNOLDS NUMBER CORRECTION IS NEEDED FOR ACCURATE NEAR-WALL Z, k AND ε PREDICTION

SOURCE TERMS IN k — EQUATION = $S_k - 2\mu \frac{k}{y^2}$

SOURCE TERMS IN ε EQUATION = $S_\varepsilon - 2\,\mu\, e^{-0.5y^+} \frac{\varepsilon}{y^2}$

$$S_\varepsilon = (C_1\, G_k - C_2\, f_2\, \rho\, \varepsilon)\ \varepsilon/k$$

$$\mu_{eff} = \mu + \mu_t\, f_\mu$$

$$f_2 = 1.0 - 0.22 \exp\,(-R_t/6)^2$$

$$f_\mu = 1.0 - \exp\,(-0.0115\ y^+)$$

$$y^+ = \rho k^{1/2}\, C_D^{1/4}\, y/\mu$$

$$R_t = \frac{\rho k^2}{\mu \epsilon}$$

63-0205-6A

EXTRA STRAIN CAUSED BY STREAMLINE CURVATURE AND SWIRL CAN BE PARTIALLY ACCOUNTED BY RICHARDSON NUMBER CORRECTION

$$C_2 = 1.92 \exp\left(-\alpha_{V_\theta} Ri_{V_\theta} - \alpha_c Ri_c\right), \quad \alpha = 0.2$$

$$Ri_c = \frac{k^2}{\epsilon^2} \frac{V_R}{R^2} \frac{\partial}{\partial R} (R V_R)$$

$$V_R = \sqrt{U^2 + V^2}$$

$$\frac{1}{R} = \frac{UV\left(\frac{\partial V}{\partial y} - \frac{\partial U}{\partial x}\right) + U^2 \frac{\partial V}{\partial x} - V^2 \frac{\partial U}{\partial y}}{V_R^{\,3}}$$

$$Ri_{V_\theta} = \frac{\left(\frac{V_\theta}{r^2}\right) \frac{\partial}{\partial r} (r V_\theta)}{\left(\frac{\partial U}{\partial r}\right)^2 + \left(r \frac{\partial}{\partial r} \left[\frac{V_\theta}{r}\right]\right)^2}$$

83-8205-7A

ALGEBRAIC REYNOLDS STRESS MODEL CORRECTLY PREDICTS INDIVIDUAL COMPONENTS IN SIMPLE FLOWS

Reynolds Stress Transport Equation

$$\left(\frac{D}{Dt} - \text{Diff}\right) u_i u_j = P_{ij} - \epsilon_{ij} + \pi_{ij}$$

Assume

$$\frac{D}{Dt}\,\overline{(u_i u_j)} - \text{Diff}\,\overline{(u_i u_j)} = \frac{\overline{u_i u_j}}{k}\left\{\frac{Dk}{Dt} - \text{Diff}(k)\right\}$$

$$= \frac{\overline{u_i u_j}}{k}\,(P - \epsilon)$$

$$\overline{u^2} = \frac{\frac{2}{3}\epsilon\,(C'_1 - 1) + \frac{2}{3}P\,(\alpha+\beta) + 2\,(1-\alpha)P}{C'_1\,\frac{\epsilon}{k} + C_{u'}\,\frac{P-\epsilon}{k}}$$

$$\overline{v^2} = \frac{\frac{2}{3}\epsilon\,(C'_1 - 1) + \frac{2}{3}P\,(\alpha+\beta) - 2\,P\beta}{C'_1\,\frac{\epsilon}{k} + C_{v'}\,\frac{P-\epsilon}{k}}$$

$$\overline{w^2} = (2k - \overline{u^2} - \overline{v^2})$$

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ALGEBRAIC REYNOLDS STRESS MODEL CORRECTLY PREDICTS INDIVIDUAL COMPONENTS IN SIMPLE FLOWS (CONTD)

$$-\overline{uv} = \left[\frac{(1-\alpha)\frac{\overline{v^2}}{k} + \gamma - \beta\frac{\overline{u^2}}{k}}{C_1'}\right]\frac{k^2}{\epsilon}\cdot\frac{\partial U}{\partial r}$$

$$-\overline{vw} = \left\{(1-\alpha)\left(\overline{v^2}\frac{\partial V_\theta}{\partial r} - \overline{w^2}\frac{V_\theta}{r} + \overline{uv}\frac{\partial V_\theta}{\partial x}\right) + \gamma k\frac{\partial V_\theta}{\partial r} + \beta\left(\overline{v^2}\frac{V_\theta}{r} - \overline{w^2}\frac{\partial V_\theta}{\partial r} - \overline{uw}\frac{\partial U}{\partial r}\right)\right\} \Big/ C_1'\frac{\epsilon}{k}$$

$$-\overline{uw} = \left\{(1-\alpha)\left(\overline{u^2}\frac{\partial V_\theta}{\partial x} + \overline{uv}\frac{\partial V_\theta}{\partial r}\right) - \beta\left(\overline{w^2}\frac{\partial V_\theta}{\partial x} - \overline{uv}\frac{V_\theta}{r}\right) - \gamma k\frac{\partial V_\theta}{\partial x}\right\} \Big/ C_1'\frac{\epsilon}{k}$$

$$C_D = \left[(1-\alpha)\frac{\overline{v^2}}{k} + \gamma - \beta\frac{\overline{u^2}}{k}\right] \Big/ C_1'$$

C_1', α, β and γ are Empirical Constants

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83-0205-0

REYNOLDS STRESS TRANSPORT MODEL SOLVES SEVEN PARTIAL DIFFERENTIAL EQUATIONS

$$\left(\frac{D}{Dt} - \text{Diff}\right) u_i u_j = S_\phi$$

$$S_{\overline{u^2}} = \frac{2}{3} \rho \epsilon (C'_1 - 1) + \frac{2}{3} G_k (\alpha + \beta) - 2(1-\alpha) \rho \overline{uv} \frac{\partial U}{\partial r}$$
$$+ 2 \rho \beta \left[\overline{uv} \frac{\partial V}{\partial x} + \overline{uw} \frac{\partial V_\theta}{\partial x} \right] - 2 \gamma \rho k \frac{\partial U}{\partial x}$$
$$- 2 \rho \overline{u^2} \frac{\partial U}{\partial x} (1 - \alpha - \beta) - C'_1 \rho \frac{\epsilon}{k} \overline{u^2}$$

$$S_{\overline{v^2}} = \frac{2}{3} \rho \epsilon (C'_1 - 1) + \frac{2}{3} G_k (\alpha + \beta) - 2 \gamma \rho k \frac{\partial V}{\partial r}$$
$$- 2 \rho (1 - \alpha) \left[\overline{uv} \frac{\partial V}{\partial x} - \overline{vw} \frac{V_\theta}{r} \right]$$
$$+ 2 \rho \beta \left[\overline{uv} \frac{\partial U}{\partial r} - \overline{vw} \frac{\partial V_\theta}{\partial r} \right]$$
$$- C'_1 \frac{\epsilon}{k} \rho \overline{v^2} - 2(1 - \alpha - \beta) \rho \overline{v^2} \frac{\partial V}{\partial r}$$

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REYNOLDS STRESS TRANSPORT MODEL SOLVES SEVEN PARTIAL DIFFERENTIAL EQUATIONS (CONTD)

$$S_{\overline{uv}} = -\rho (1-\alpha) \left[\overline{v^2} \frac{\partial U}{\partial r} - \overline{uw} \frac{V_\theta}{r} + \overline{u^2} \frac{\partial V}{\partial x} \right]$$

$$+ \rho \beta \left[\overline{v^2} \frac{\partial V}{\partial x} + \overline{vw} \frac{\partial V_\theta}{\partial x} + \overline{uw} \frac{\partial V_\theta}{\partial r} + \overline{u^2} \frac{\partial U}{\partial r} \right]$$

$$- \rho \gamma k \left(\frac{\partial U}{\partial r} + \frac{\partial V}{\partial x} \right) + \rho \overline{uv} \frac{V}{r} (1 - \alpha - \beta) - C_1' \frac{\rho \epsilon}{k} \overline{uv}$$

$$S_{\overline{vw}} = -\rho (1-\alpha) \left[\overline{v^2} \frac{\partial V_\theta}{\partial r} - \overline{w^2} \frac{V_\theta}{r} + \overline{uv} \frac{\partial V_\theta}{\partial x} + \overline{uw} \frac{\partial V}{\partial x} \right]$$

$$+ \rho \beta \left[\overline{w^2} \frac{\partial V_\theta}{\partial r} + \overline{uw} \frac{\partial U}{\partial r} - \overline{v^2} \frac{V_\theta}{r} \right] - \rho \gamma k \frac{\partial V_\theta}{\partial r}$$

$$+ \rho \overline{vw} \frac{\partial U}{\partial x} (1 - \alpha - \beta) - C_1' \frac{\rho \epsilon}{k} \overline{vw}$$

$$S_{\overline{uw}} = -\rho (1-\alpha) \left[\overline{vw} \frac{\partial U}{\partial r} + \overline{u^2} \frac{\partial V_\theta}{\partial x} + \overline{uv} \frac{\partial V_\theta}{\partial r} \right]$$

$$+ \rho \beta \left[\overline{vw} \frac{\partial V}{\partial x} + \overline{w^2} \frac{\partial V_\theta}{\partial x} - \overline{uv} \frac{V_\theta}{r} \right]$$

$$- \rho \gamma k \frac{\partial V_\theta}{\partial x} - C_1' \frac{\rho \varepsilon}{k} \overline{uw} + \rho \overline{uw} (1 - \alpha - \beta) \frac{\partial V}{\partial r}$$

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63-0205-11A

SCALAR TRANSPORT PROCESSES MUST BE MODELED PROPERLY TO ACCURATELY PREDICT REACTION RATES

Assume Constant σ_f

$$\nabla \cdot \left(\rho V f - \frac{\mu_{eff}}{\sigma_f} \nabla f\right) = S_f$$

Scalar Transport Equations:
k-ε Model Uses Gradient Diffusion Assumption

$$\rho \overline{u\theta'} = - \Gamma_{eff,\theta} \frac{\partial \overline{\theta}}{\partial x}$$

$$\rho \overline{v\theta'} = - \Gamma_{eff,\theta} \frac{\partial \overline{\theta}}{\partial r}$$

$$\rho \overline{\theta'^2} = \frac{2}{\alpha_\theta} \frac{k}{\epsilon} \Gamma_{eff,\theta} \left[\left(\frac{\partial \overline{\theta}}{\partial x}\right)^2 + \left(\frac{\partial \overline{\theta}}{\partial r}\right)^2\right]$$

where

$$\Gamma_{eff,\theta} = \mu_{eff}/\sigma_\theta$$

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THE ALGEBRAIC SCALAR TRANSPORT MODEL PREDICTS COUNTER-GRADIENT DIFFUSION OF SCALAR IN SIMPLE FLOWS

Transport Equations for $\overline{u_j\theta'}$:

$$\underbrace{\mathrm{Div}\,(\rho\vec{v}\;\overline{u_j\theta'})}_{\text{Convection}} - \underbrace{\mathrm{Diff}\,(\rho\,\overline{u_j\theta'})}_{\text{Diffusion}} = \underbrace{\rho P_{j\theta}}_{\text{Production}} - \underbrace{\rho\epsilon_{j\theta}}_{\text{Dissipation}} + \underbrace{\rho\psi_{j\theta}}_{\text{Redistribution}}$$

Assumption:

$$\mathrm{Div}\left(\rho\vec{v}\;\overline{u_j\theta'}\right) - \mathrm{Diff}\left(\rho\overline{u_j\theta'}\right) = a_1\frac{\overline{u_j\theta'}}{k}(P-\epsilon) + a_2\frac{\overline{u_j\theta'}}{\overline{\theta'^2}}(P_\theta - \epsilon_\theta)$$

where:

$$P_\theta = -2\,\overline{u_j\theta'}\,\frac{\partial\bar{\theta}}{\partial x_j}$$

$$\epsilon_\theta = \alpha_\theta\,\frac{\epsilon}{k}\,\overline{\theta'^2}$$

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THE ALGEBRAIC SCALAR TRANSPORT MODEL PREDICTS COUNTER-GRADIENT DIFFUSION OF SCALAR IN SIMPLE FLOWS (CONTD)

The transport equation for scalar fluctuations, $\overline{\theta'^2}$, is

$$\underbrace{\mathrm{div}\,(\rho\vec{v}\,\overline{\theta'^2})}_{\text{Convection}} - \underbrace{\mathrm{Diff}\,(\rho\overline{\theta'^2})}_{\text{Diffusion}} = \underbrace{\rho P_\theta}_{\text{Production}} - \underbrace{\rho\epsilon_\theta}_{\text{Dissipation}}$$

Assume:

$$\mathrm{div}\,(\rho\vec{v}\,\overline{\theta'^2}) - \mathrm{Diff}\,(\rho\overline{\theta'^2}) \approx C_\theta \frac{\rho\overline{\theta'^2}}{k}(P-\epsilon)$$

$$-\overline{v\theta'} = \left[\overline{uv}\,\frac{\partial\bar{\theta}}{\partial x} + \overline{v^2}\,\frac{\partial\bar{\theta}}{\partial r}\right] \Big/ \left[c_{1\theta}\,\frac{\epsilon}{k} + a_1\left(\frac{P-\epsilon}{k}\right)\right]$$

$$-\overline{u\theta'} = \left[\overline{u^2}\,\frac{\partial\bar{\theta}}{\partial x} + \overline{uv}\,\frac{\partial\bar{\theta}}{\partial r} + \overline{v\theta'}\,\frac{\partial U}{\partial r}(1-c_{2\theta})\right] \Big/ \left[a_1\left(\frac{P-\epsilon}{k}\right) + c_{1\theta}\,\frac{\epsilon}{k} + (1-c_{2\theta})\,\frac{\partial U}{\partial x}\right]$$

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83-0205-14

THE ALGEBRAIC SCALAR TRANSPORT MODEL PREDICTS COUNTER-GRADIENT DIFFUSION OF SCALAR IN SIMPLE FLOWS (CONTD)

$$\overline{\theta'^2} = -2\left[\overline{u\theta'}\frac{\partial\bar{\theta}}{\partial x} + \overline{v\theta'}\frac{\partial\bar{\theta}}{\partial r}\right] \Big/ \left[c_\theta\left(\frac{P-\epsilon}{k}\right) + \alpha_\theta\frac{\epsilon}{k}\right]$$

Recommended Values For Model Constants:

$C_{1_\theta} = 1.6$, $C_{2_\theta} = 0.5$, $\alpha_\theta = 1.25$, $C_\theta = 0.8$, $a_1 = 0.8$

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63-0205-15

DATA BASE FOR IDEAL ELEMENT TESTS COMPILED FROM A LITERATURE SURVEY

- DATA BASE COMPILED FOR THE FOLLOWING SUBMODELS:
  - TURBULENCE MODELING
  - GASEOUS COMBUSTION
  - SPRAY EVAPORATION AND COMBUSTION
  - SOOT FORMATION AND OXIDATION

63-0205-16

DATA BASE FOR IDEAL ELEMENT TESTS COMPILED FROM A LITERATURE SURVEY (CONTD)

- FOR ALL CASES, THE DATA BASE IS ORGANIZED IN INCREASING ORDER OF COMPLEXITY OF THE FLOW. FOR TURBULENCE MODELING THE CATEGORIES ARE
  - SIMPLE FLOWS (BOUNDARY LAYERS, MIXING LAYERS, ETC.)
  - STREAMLINE CURVATURE EFFECTS (CURVED DUCTS, CURVED BOUNDARY LAYERS, ETC.)
  - RECIRCULATING FLOWS (NONSWIRLING) (BOTH UNCONFINED AND CONFINED)
  - SWIRLING FLOWS (WITH AND WITHOUT RECIRCULATION)
  - SCALAR TRANSPORT

63-0205-17A

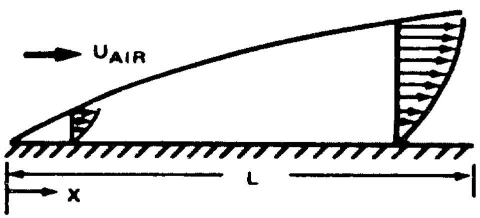
DATA BASE FOR IDEAL ELEMENT TESTS COMPILED FROM A LITERATURE SURVEY (CONTD)

- IN GASEOUS COMBUSTION, THE DATA BASE IS CATEGORIZED INTO
  - LAMINAR PREMIXED FLAMES
  - LAMINAR DIFFUSION FLAMES
  - TURBULENT PREMIXED FLAMES
  - TURBULENT DIFFUSION FLAMES
- DATA BASE FROM GARRETT GAS TURBINE COMBUSTORS IS INCLUDED

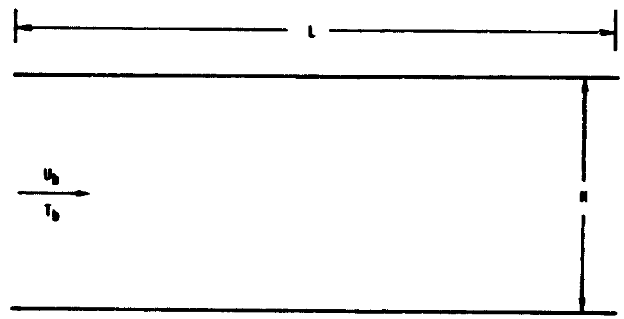
63-0205-18

A NUMBER OF SIMPLE FLOWS HAVE BEEN ANALYZED

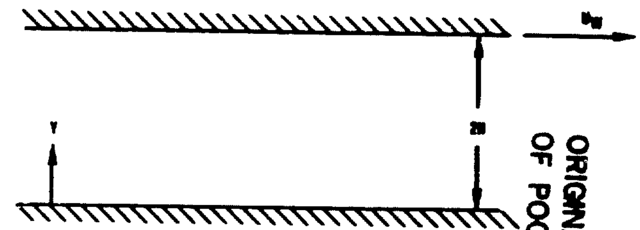
WATTS AND BRUNDRETT
FLOW OVER A FLAT PLATE



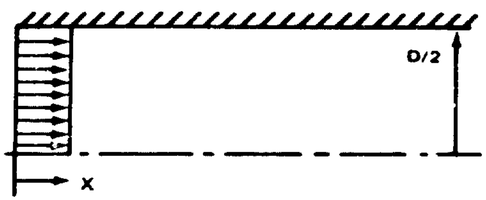
EMERY AND GESSNER
2-D CHANNEL FLOW



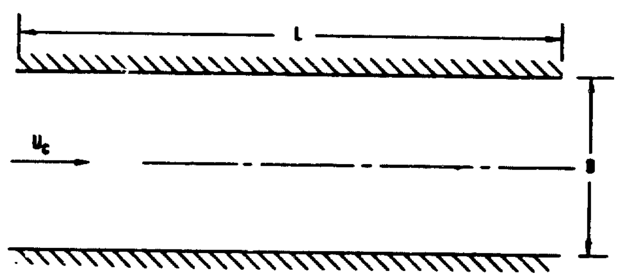
EL TELBANY AND REYNOLDS
COUETTE FLOW



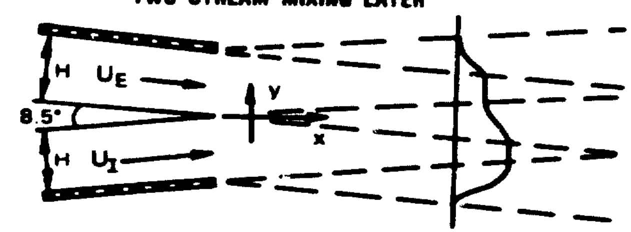
BARBIN AND JONES
DEVELOPING PIPE FLOW



LAUFER PIPE FLOW



SAIY AND PEERLESS
TWO STREAM MIXING LAYER



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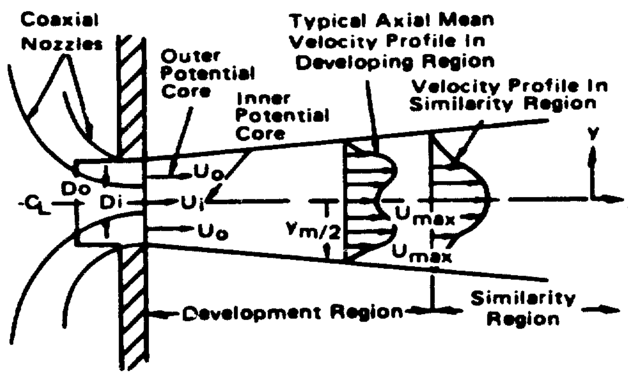
A NUMBER OF SIMPLE FLOWS HAVE BEEN ANALYZED (CONTD)

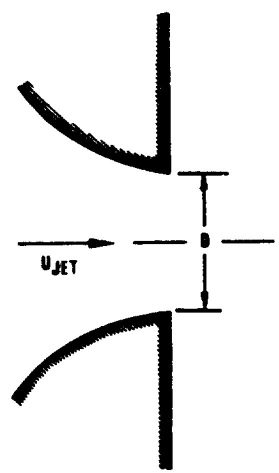
CHAMPAGNE AND WYGNANSKI

MIXING OF TWO COAXIAL JETS IN AMBIENT AIR



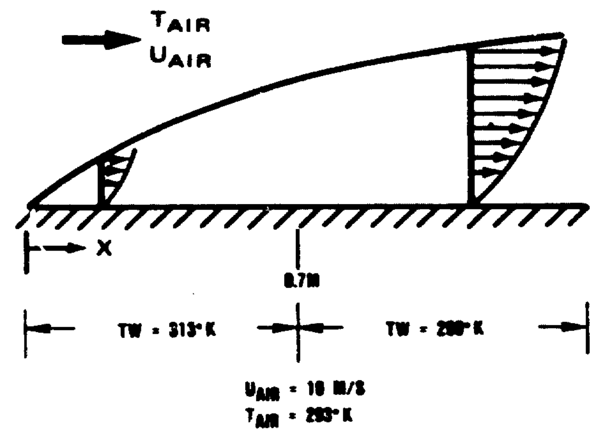
WYGNANSKI AND FIEDLER

AXISYMMETRIC FREE JET



CHARNAY ET AL

FLOW OVER A HEATED FLAT PLATE



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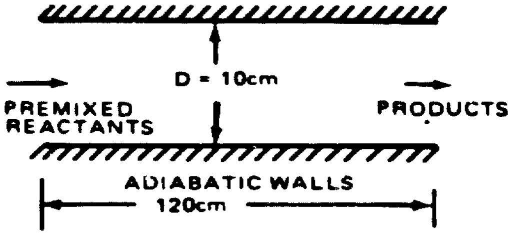
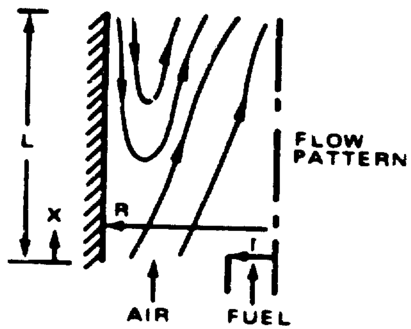
A NUMBER OF SIMPLE FLOWS HAVE BEEN ANALYZED (CONTD)

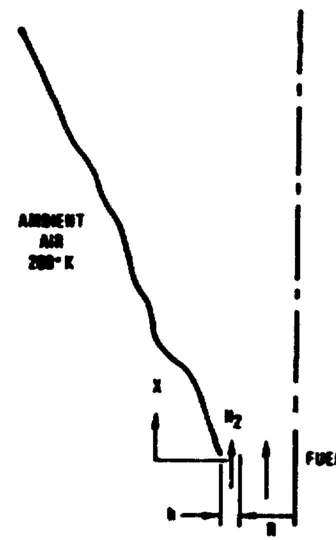
HAUTMAN ET AL
PLUG FLOW REACTOR



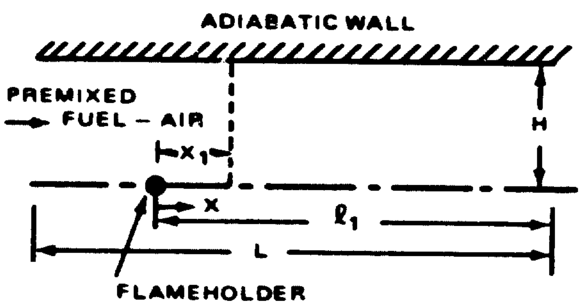
MITCHELL ET AL
CONCENTRIC FUEL AND AIR JETS
CONTAINED IN A CYLINDRICAL COMBUSTOR



HASSAN AND LOCKWOOD
FREE METHANE TURBULENT JET FLAME



SHIPMAN AND CO-WORKERS
CONFINED STOICHIOMETRIC FLAME STABILIZED ON A CYLINDRICAL FLAMEHOLDER IN A RECTANGULAR DUCT



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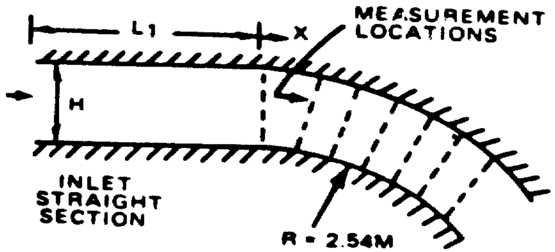
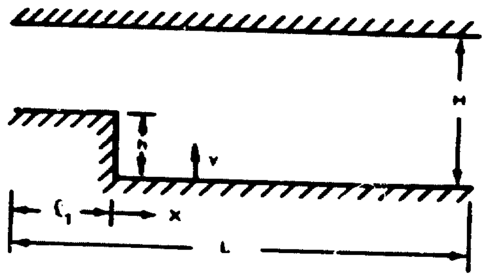
A NUMBER OF COMPLEX NONSWIRLING FLOWS HAVE BEEN INVESTIGATED

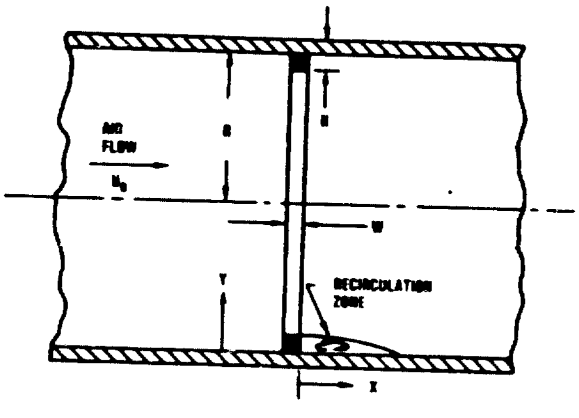
SHIVA-PRASAD AND RAMA-PRIYAN
FLOW IN A CURVED CHANNEL



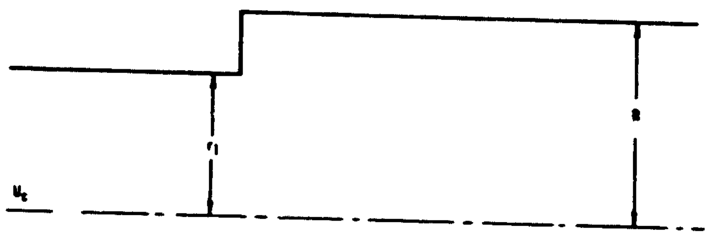
KIM, KLINE, AND JOHNSTON (1978) AND EATON AND JOHNSTON
FLOW OVER A BACKWARD FACING PLANE STEP



PHATARAPHRUK AND LOGAN
FLOW OVER A RING IN A PIPE



MOON AND RUDINGER
SUDDEN PIPE-EXPANSION



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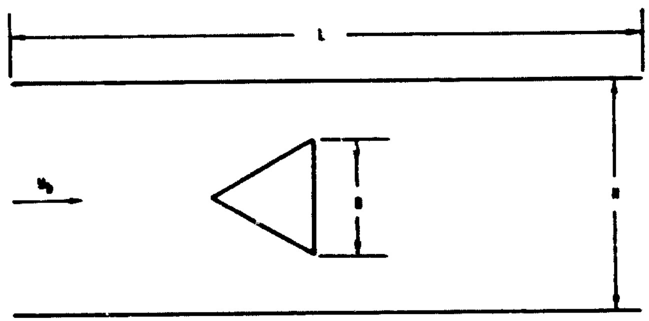
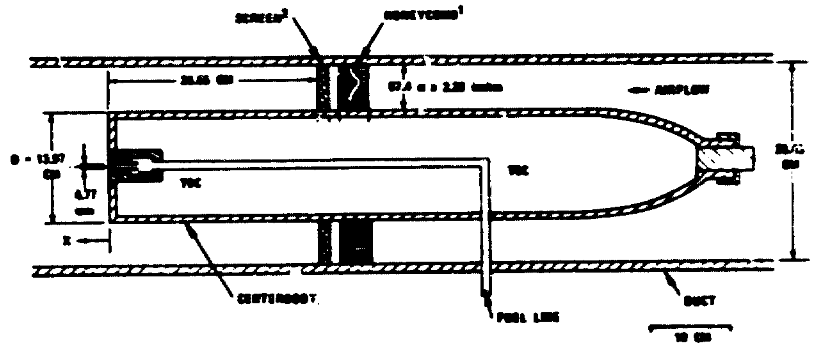
G3-0205-22

A NUMBER OF COMPLEX NONSWIRLING FLOWS HAVE BEEN INVESTIGATED (CONTD)

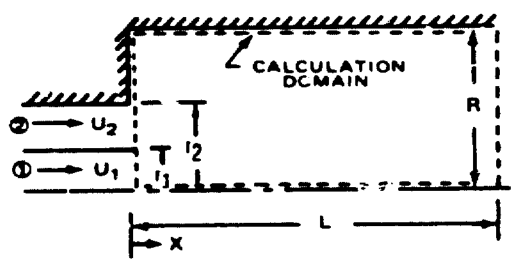
WEDGE-SHAPED FLAMEHOLDER



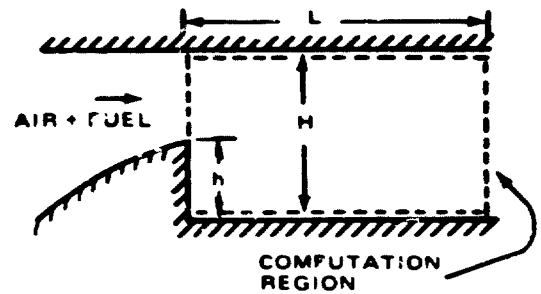
APL COMBUSTION TUNNEL



JOHNSON AND BENNETT
FLOW THROUGH A SUDDEN EXPANSION IN A PIPE



PITZ AND DAILY
FLOW BEHIND A BACKWARD FACING STEP



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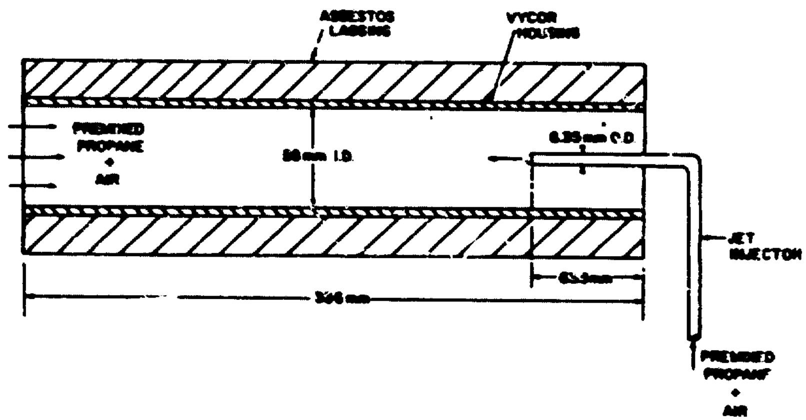
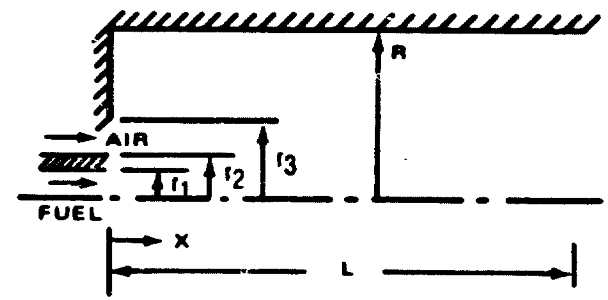
63-0205-22

A NUMBER OF COMPLEX NONSWIRLING FLOWS HAVE BEEN INVESTIGATED (CONTD)

SCHEFFER AND SAWYER
OPPOSED JET COMBUSTOR



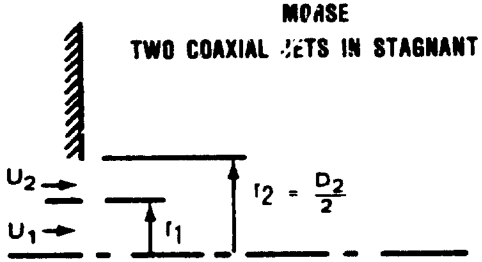
LEWIS AND SMOOT
AXISYMMETRIC COMBUSTOR WITH COAXIAL FUEL AND AIR JETS



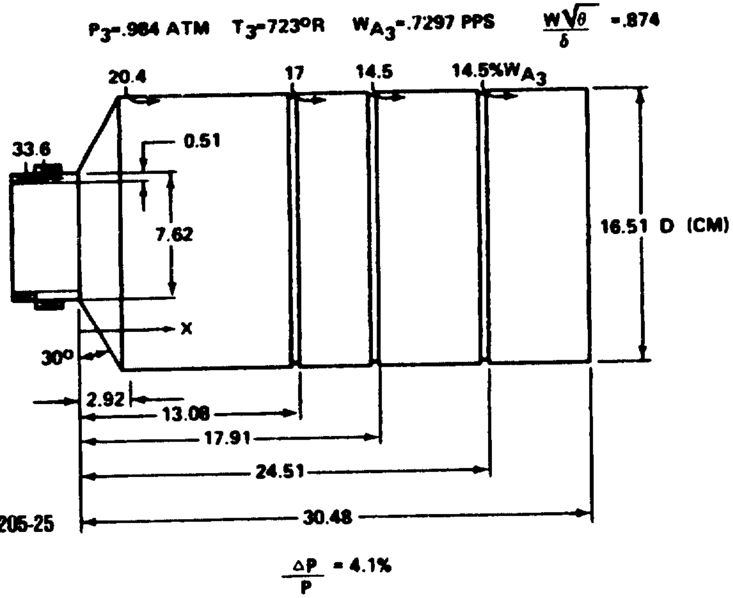
63-0205-24

A NUMBER OF SWIRLING FLOWS HAVE BEEN INVESTIGATED

MORSE
TWO COAXIAL JETS IN STAGNANT AIR

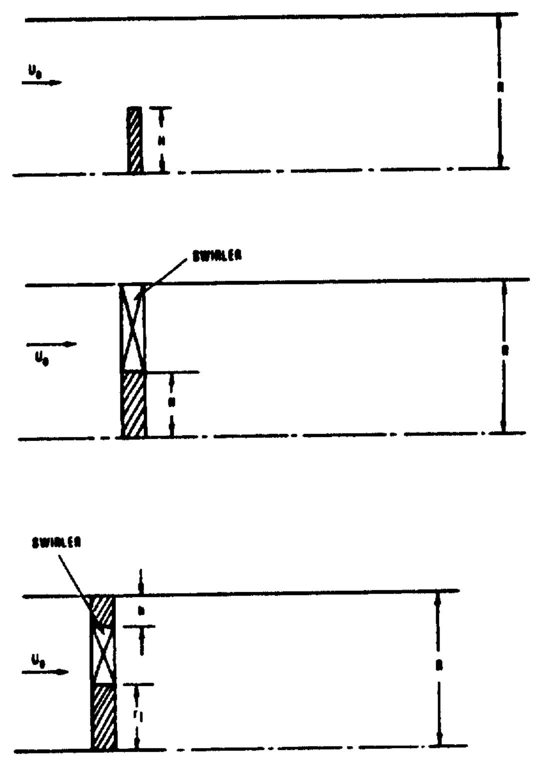


GTEC
NONREACTING SWIRLING COMBUSTOR



G3-0205-25

GTEC
SWIRLING FLOW INVESTIGATION



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GARRETT

A NUMBER OF SWIRLING FLOWS HAVE BEEN INVESTIGATED (CONTD)

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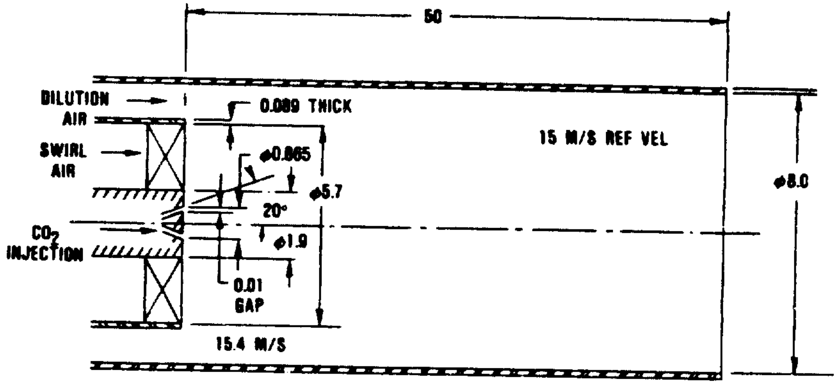
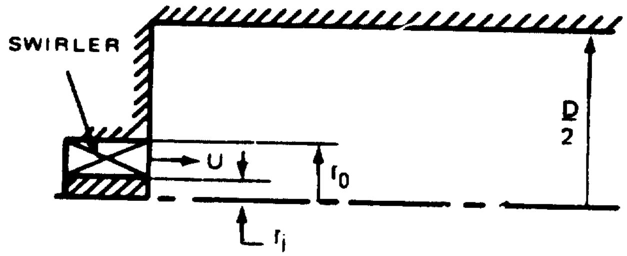
BRUM AND SAMUELSEN
SWIRL COMBUSTOR WITH COOLING AIR



ALL DIMENSIONS IN CM

JANJUA ET AL
SWIRLING FLOW IN A PIPE EXPANSION

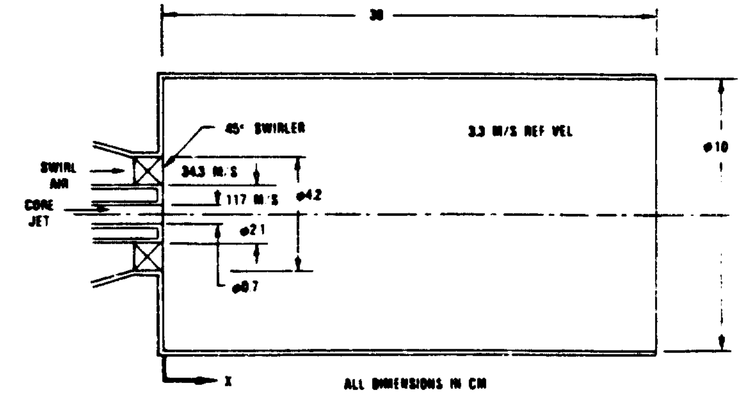


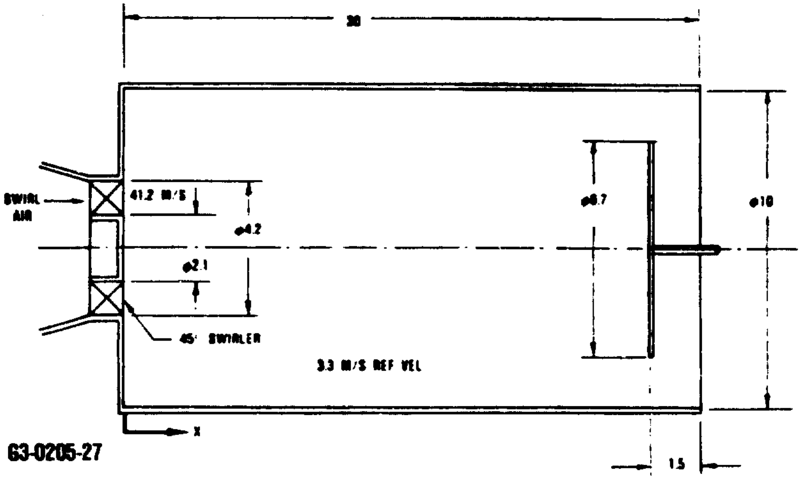
63-0205-26

A NUMBER OF SWIRLING FLOWS HAVE BEEN INVESTIGATED (CONTD)

ALTGELD, JONES, AND WILHELMI

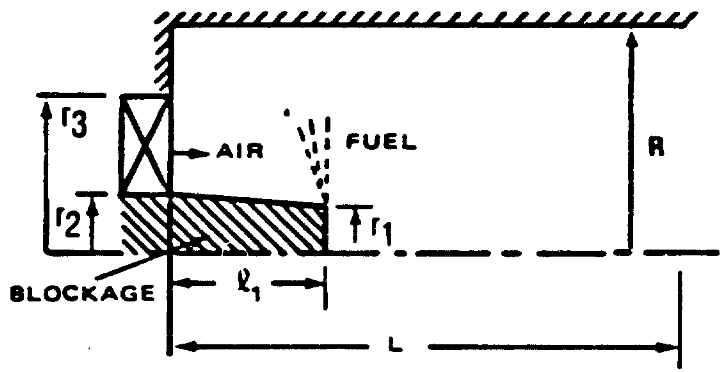
CONFINED SWIRL-DRIVEN FLOW



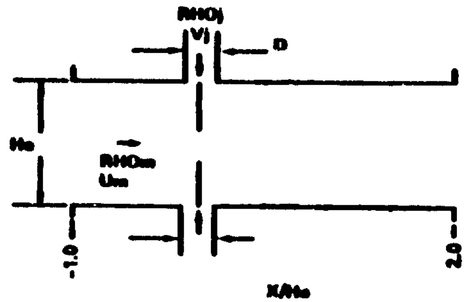


EL-BANHAWY AND WHITELAW

CYLINDRICAL COMBUSTOR WITH ROTATING CUP ATOMIZER AND AIR INTRODUCED THROUGH A SWIRLER SURROUNDING THE ATOMIZER



3-D DILUTION JET MIXING CALCULATIONS



- DILUTION JET MIXING 3-D CASES

		JET DIAMETER, D (CM)	S/D	Ho/D	J
SINGLE SIDED INJECTION		1.27	2	8	25.32
		1.27	2	8	107.78
		1.8	2.83	5.66	25.48
		2.54	2	4	21.59
		2.54	4	4	26.68
		2.54	4	4	6.14
PROFILED MAINSTREAM TEMPERATURE		2.54	2	4	22.63
IN-LINE	TOP	1.27	2	8	24.95
	BOTTOM	1.27	2	8	24.76
STAGGERED	TOP	2.54	4	4	26.4
	BOTTOM	2.54	4	4	26.1

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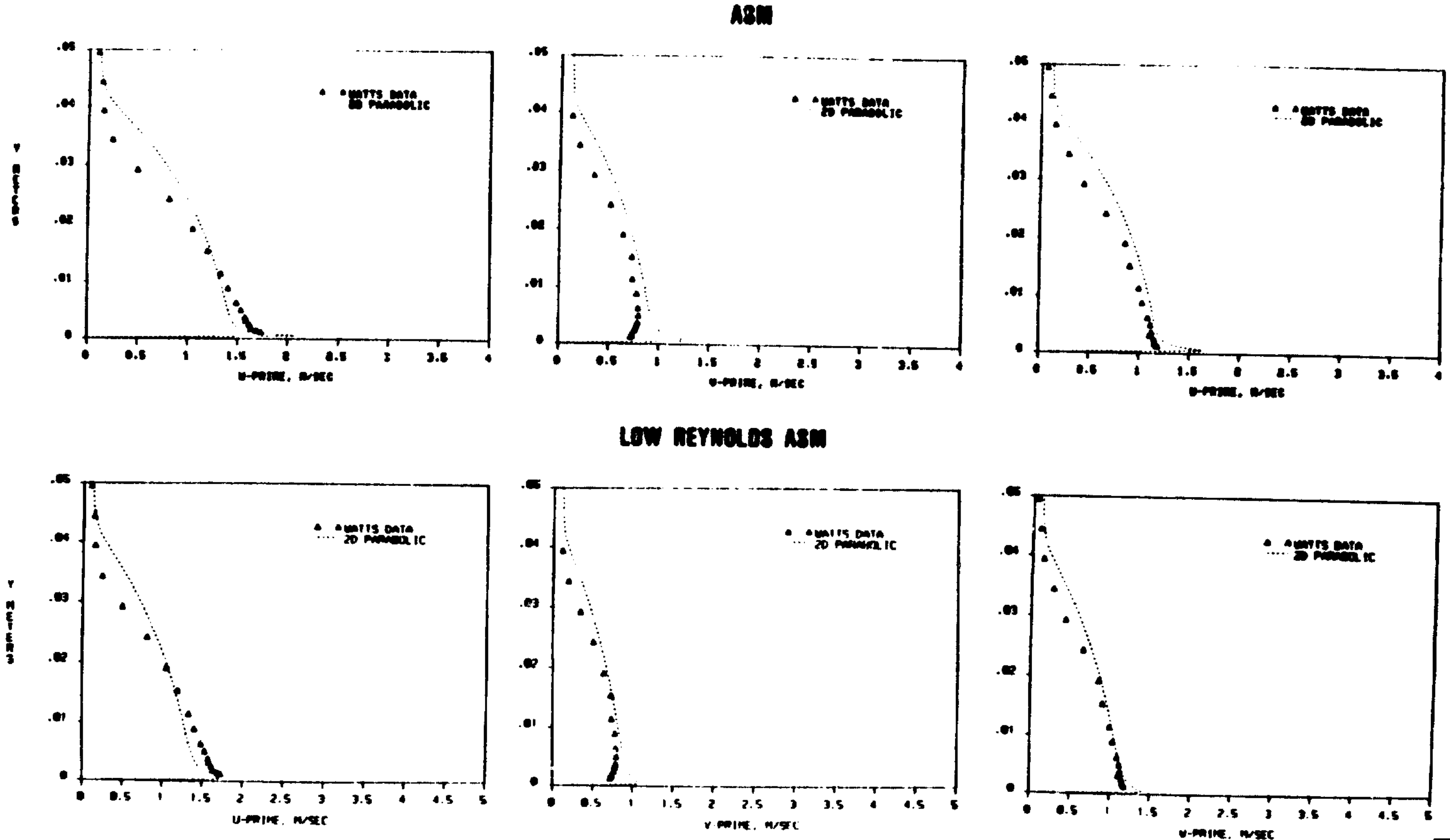
EFFECTS OF LOW REYNOLDS NUMBER CORRECTION ON ASM PREDICTIONS FOR FLAT PLATE BOUNDARY LAYER; X = 1.8735 M



83-0281-1

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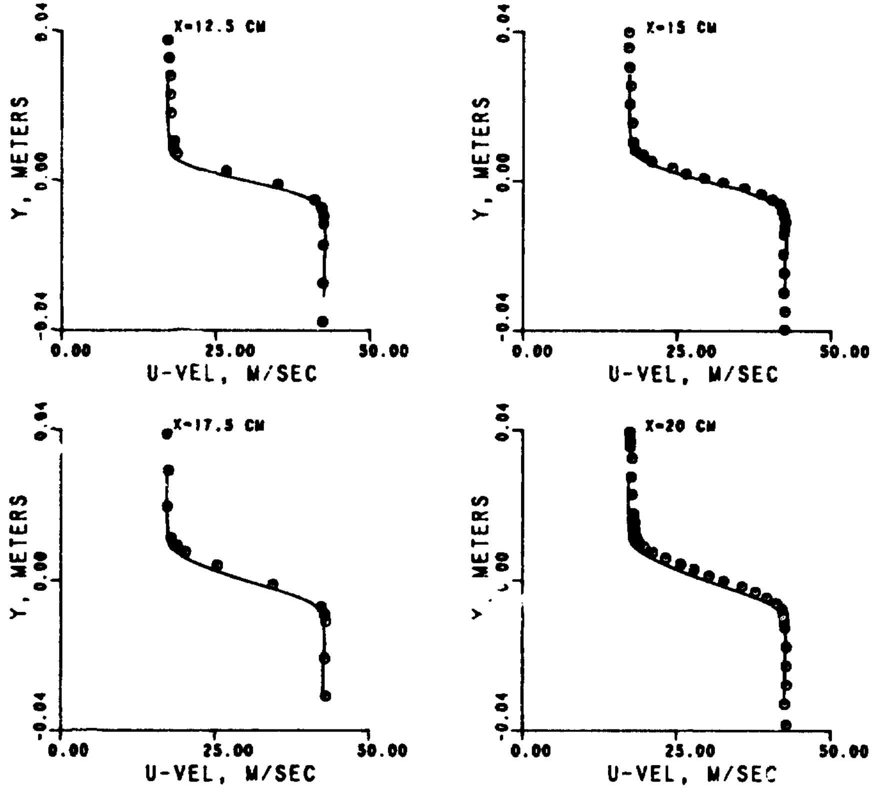
ASM PREDICTIONS FOR TWO-STREAM MIXING LAYER; $U_E/U_I = 0.43$



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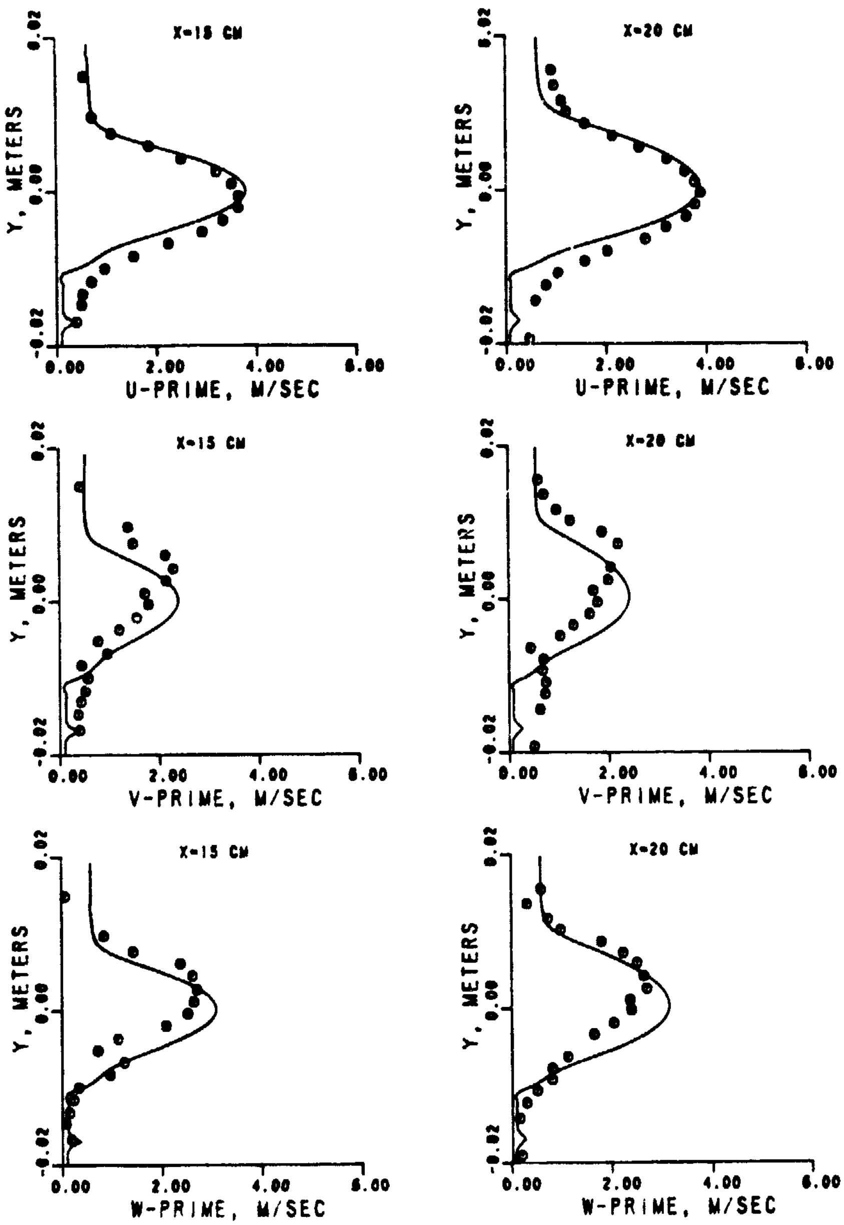
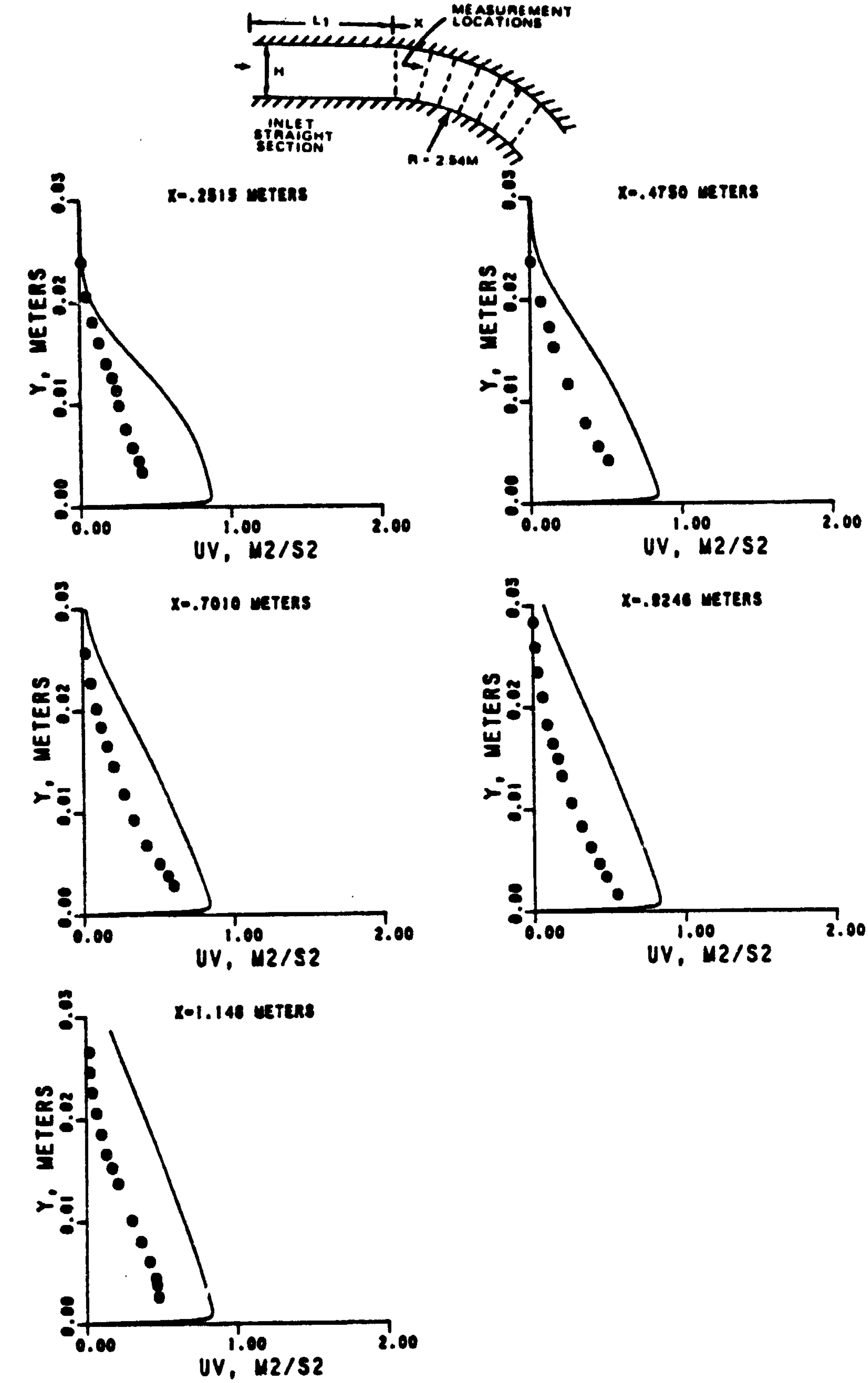
63-0281-2

ASM PREDICTIONS FOR TWO-STREAM MIXING LAYER, UE/UI = 0.43



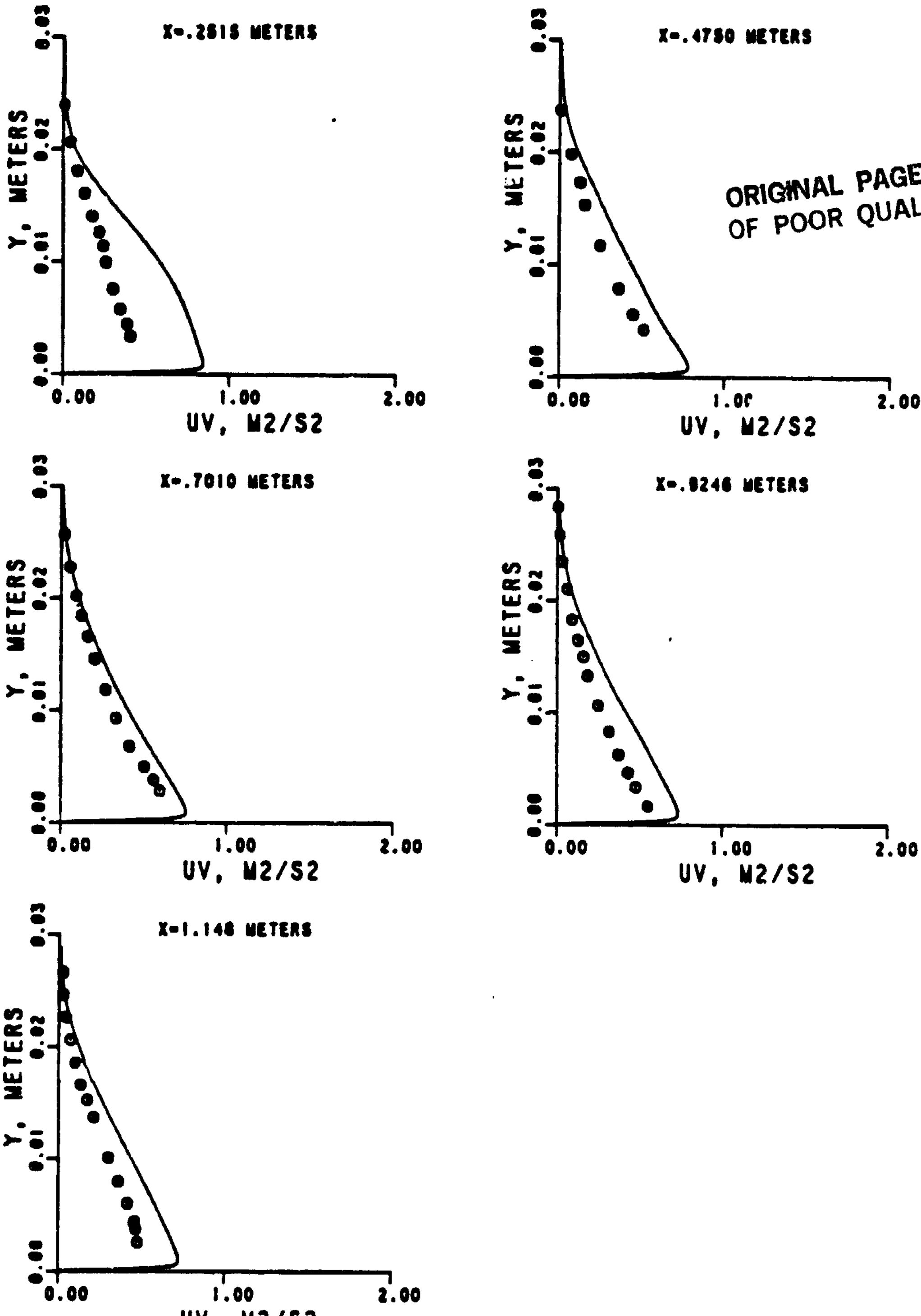
63-0281-3

ASM PREDICTIONS FOR CONVEX WALL BOUNDARY LAYER



G3-0281-4

PREDICTIONS FROM ASM WITH STREAMLINE CURVATURE CORRECTION ALONG CONVEX (INNER) WALL



83-0281-5

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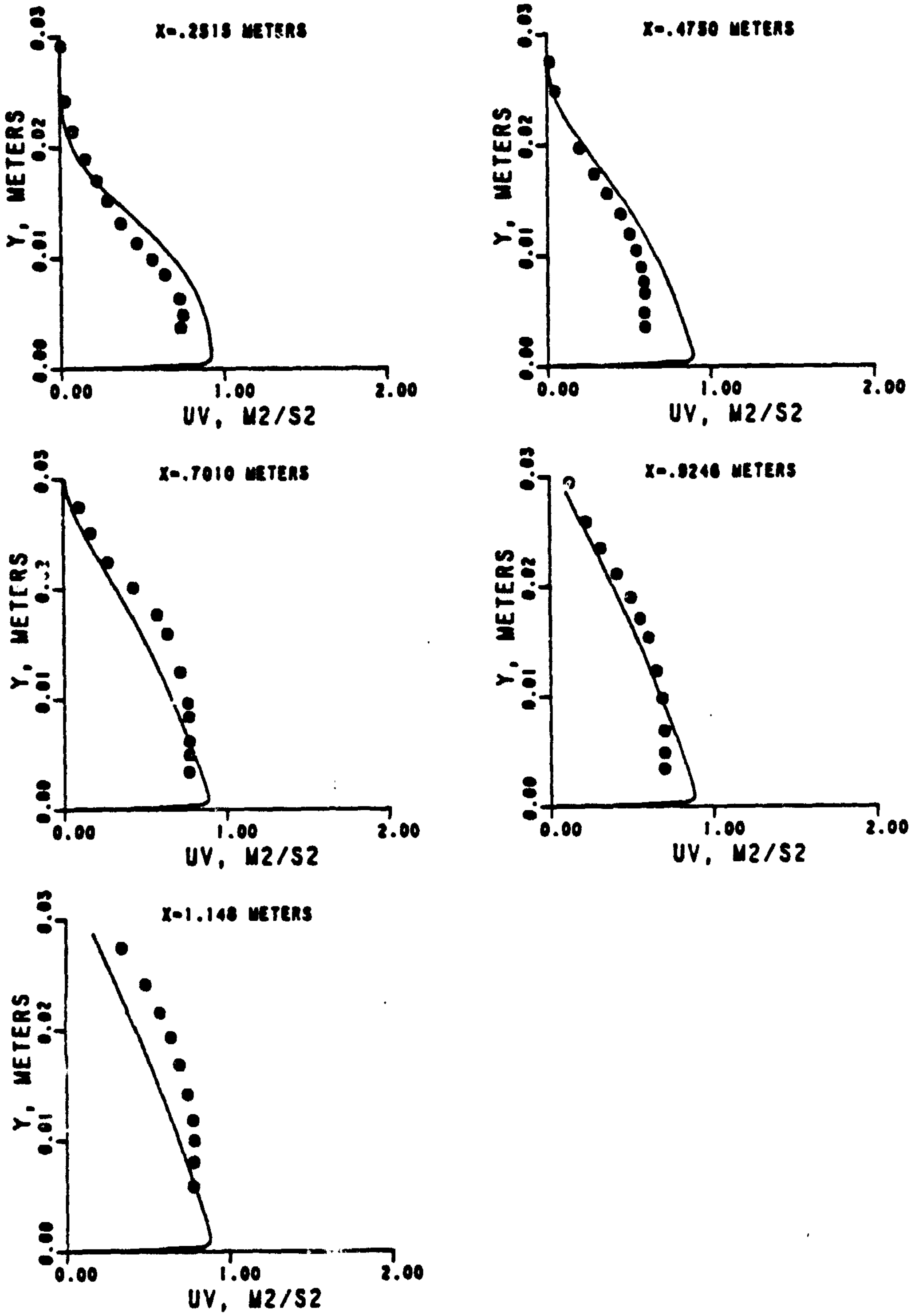
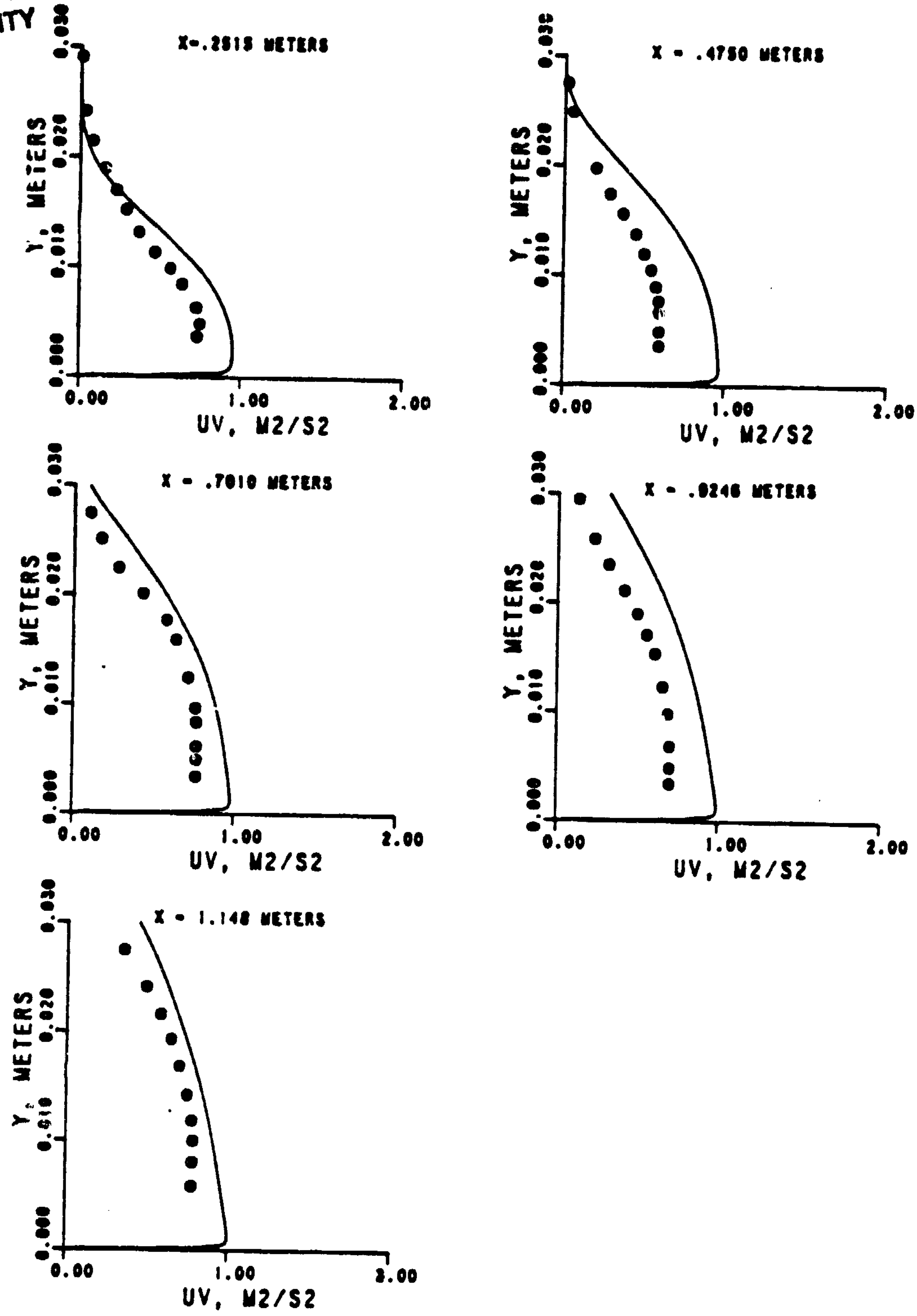
ASM PREDICTIONS AND DATA FOR (OUTER) CONCAVE WALL BOUNDARY LAYER



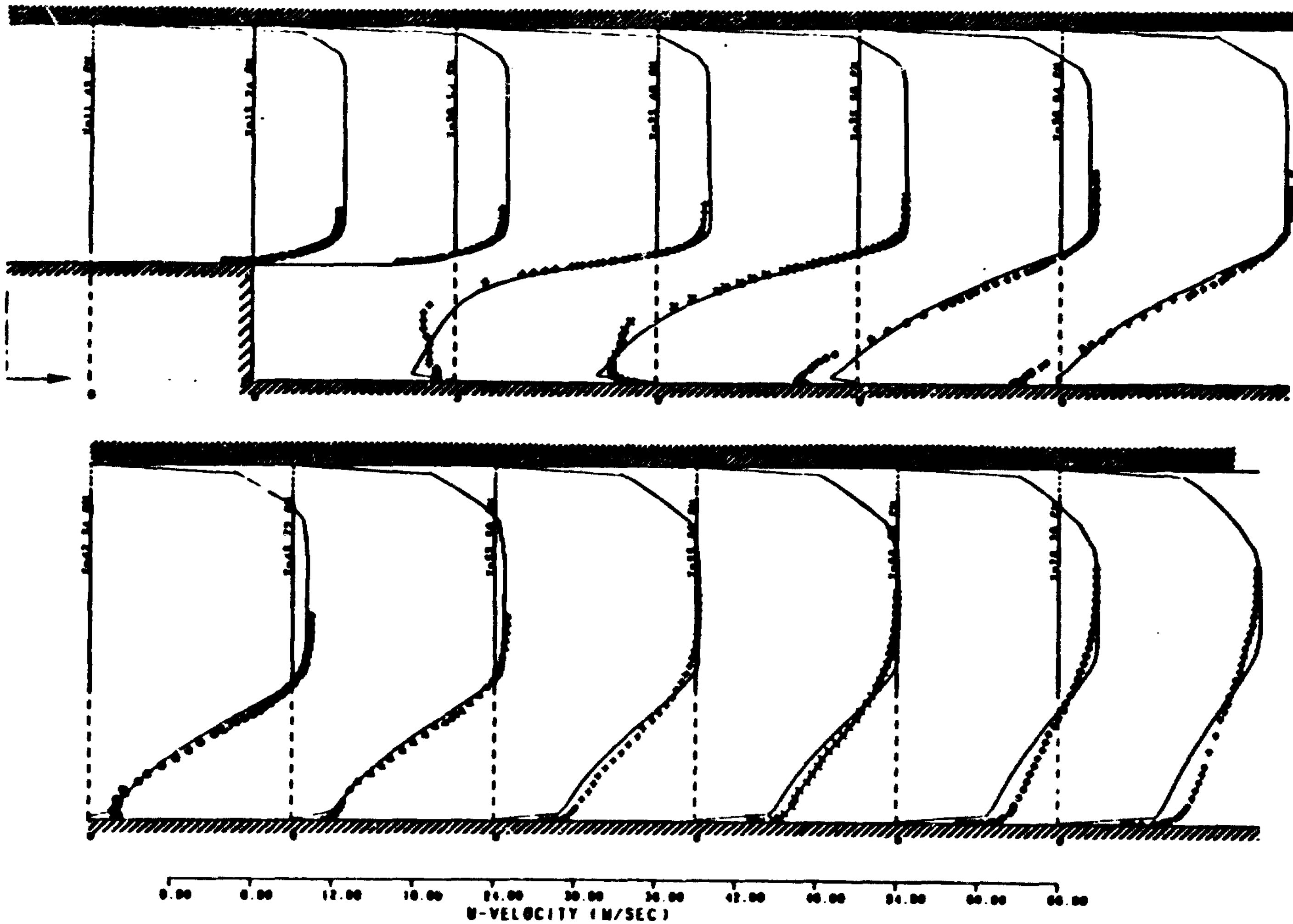
63-0281-6

PREDICTIONS BY ASM WITH STREAMLINE CURVATURE CORRECTIONS FOR (OUTER) CONCAVE WALL BOUNDARY LAYER



83-0281-7

COMPARISON BETWEEN DATA AND PREDICTIONS BY ASM WITH STREAMLINE CURVATURE CORRECTIONS FOR FLOW BEHIND 3.81 CM STEP



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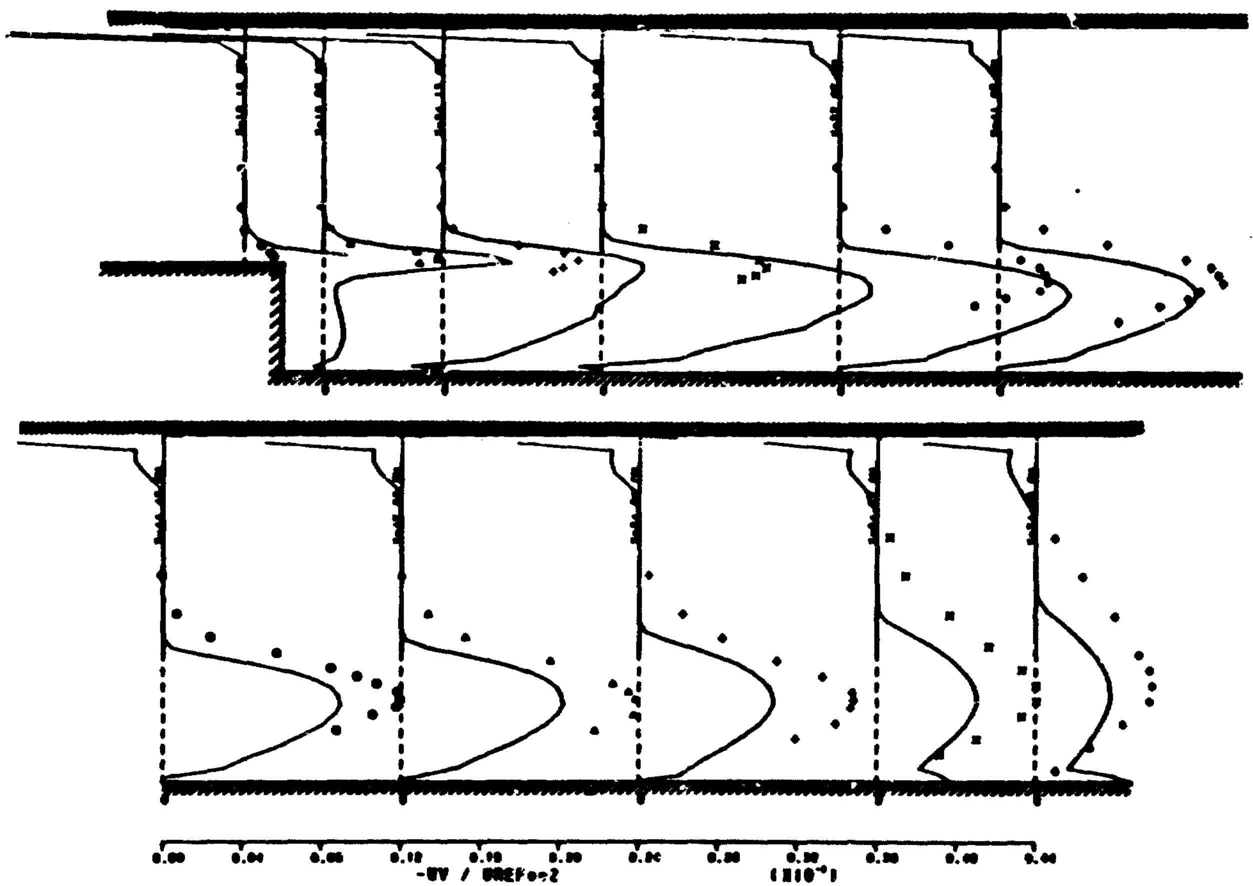
63-0281-8

COMPARISON BETWEEN DATA AND PREDICTIONS BY ASM WITH STREAMLINE CURVATURE CORRECTIONS FOR FLOW BEHIND 3.81 CM STEP



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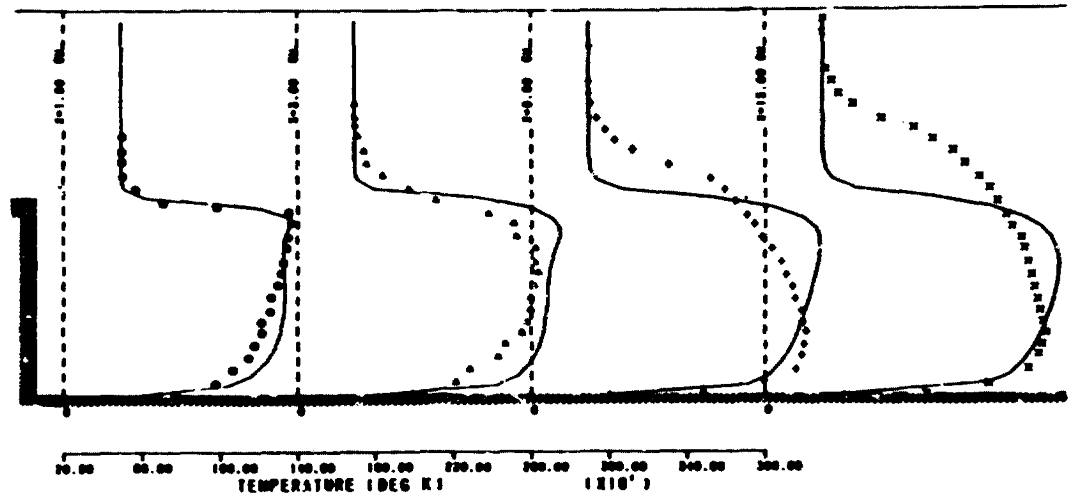
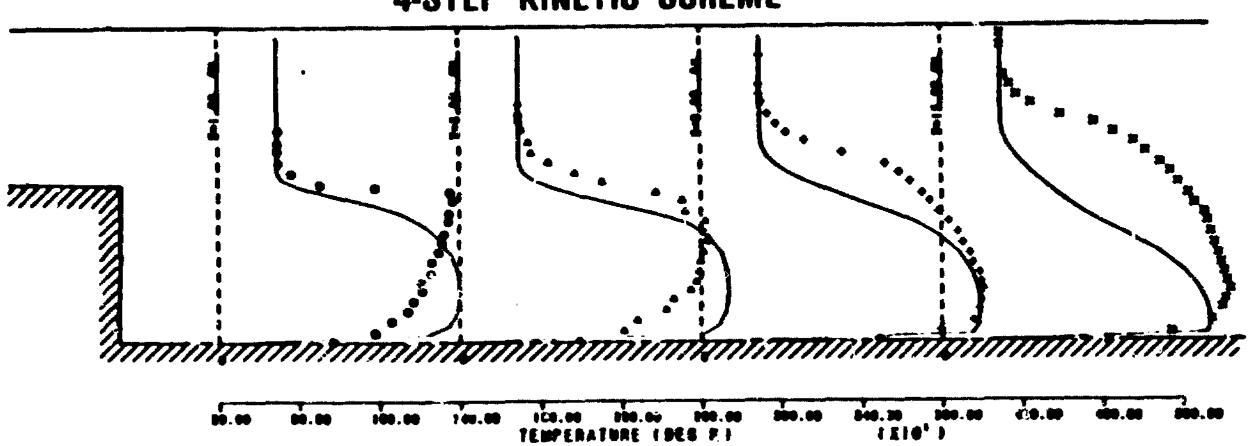
83-0281-10

STANDARD K-ε MODEL PREDICTIONS FOR PREMIXED PROPANE/AIR GAS FLOW BEHIND 2.54 CM STEP; $\phi = 0.56$

2-STEP KINETIC SCHEME



4-STEP KINETIC SCHEME



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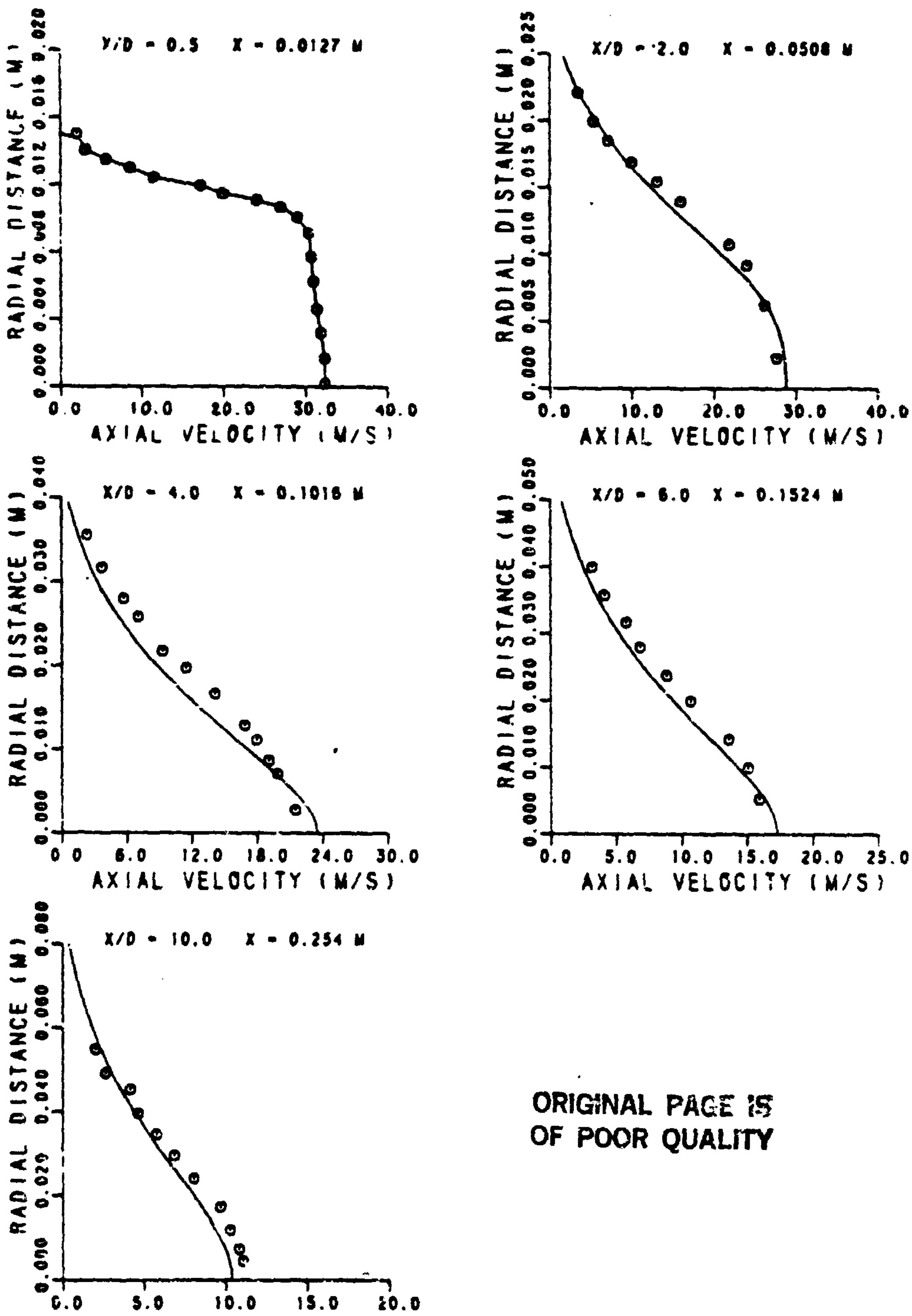
63-0281-11 A

COMPARISON BETWEEN DATA AND K-ε MODEL PREDICTIONS FOR FREE SWIRLING JET; SWIRL NUMBER = 0.25



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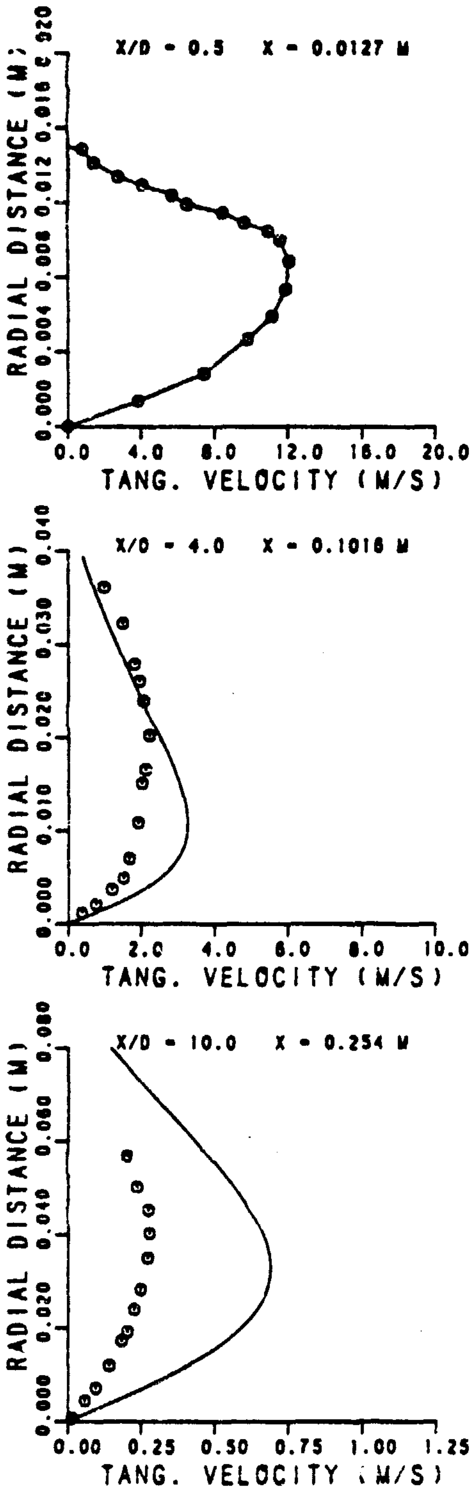
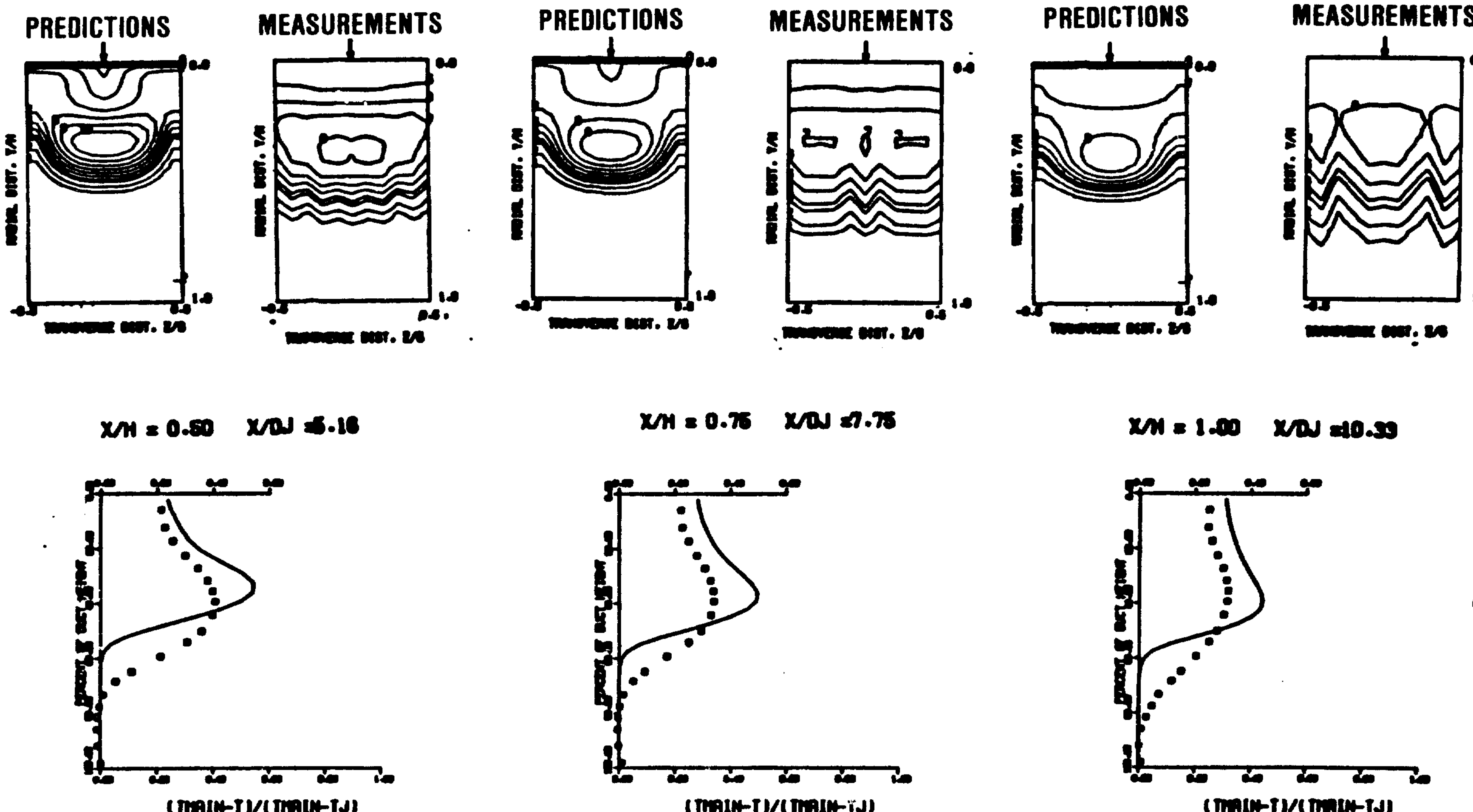
83-0281-12

COMPARISON BETWEEN DATA AND K-ε MODEL PREDICTIONS FOR FREE SWIRLING JET; SWIRL NUMBER = 0.25



83-0281-13

COMPARISON BETWEEN DATA AND PREDICTIONS USING 20,000 NODES FOR J = 25.32, S/D = 2.00, H/D = 8.00



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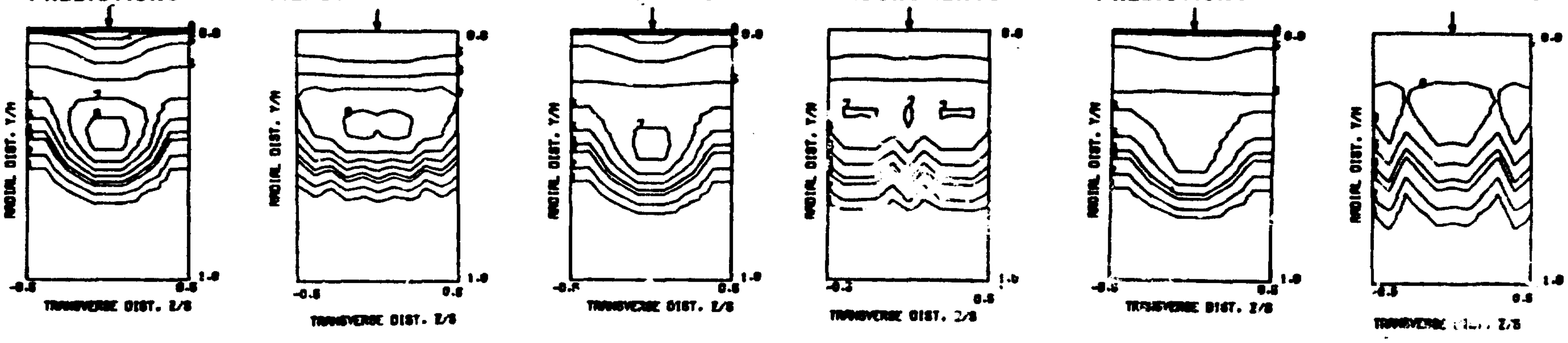
63-0281-14

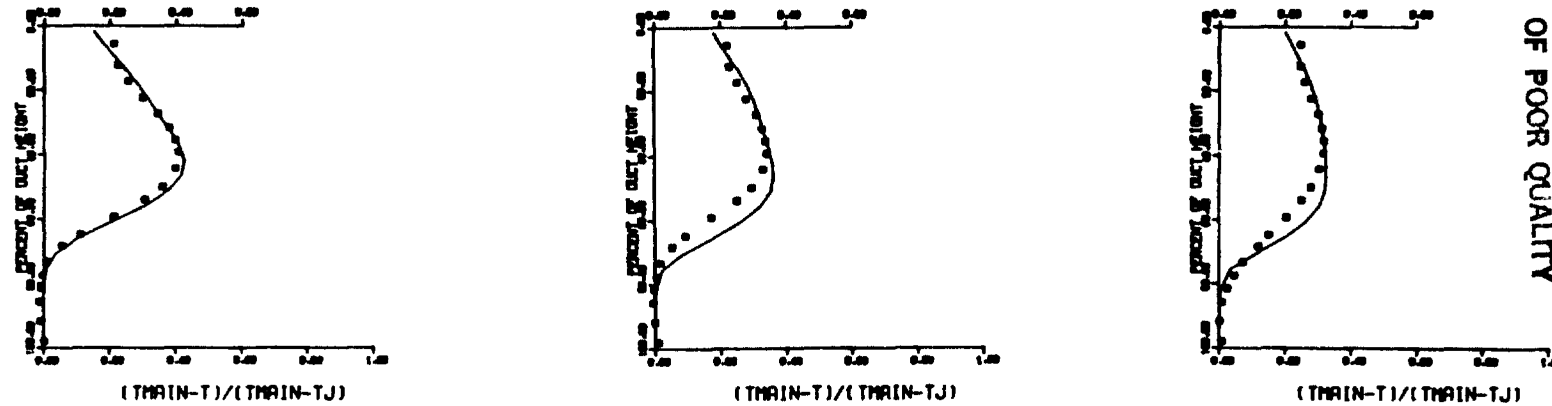
COMPARISON BETWEEN DATA AND PREDICTIONS USING 6000 NODES FOR J = 25.32, S/D = 2.00, H/D = 8.00



X/H = 0.50 X/DJ =5.16

X/H = 0.75 X/DJ =7.75

X/H = 1.00 X/DJ =10.33



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G3-0281-23

k-ε MODEL AND ITS MODIFICATIONS

- GIVES GOOD CORRELATION OF MEAN VALUES FOR
  - SIMPLE FLOWS
  - FAR-FIELD REGIMES OF NONSWIRLING/SWIRLING FLOWS INVOLVING REGIONS OF RECIRCULATION
  - NONRECIRCULATING SWIRLING FLOWS
  - OUTER REGIONS OF STRONG SWIRLING FLOWS
- GIVES REASONABLE CORRELATION OF MEAN VALUES FOR
  - NONSWIRLING RECIRCULATING FLOWS EXCLUDING VICINITY OF REATTACHMENT POINT
  - CONFINED DISK FLOW WITH A CENTRAL JET
  - SHEAR LAYER OF STRONG SWIRLING FLOWS
  - CONFINED SWIRLER WITH HUB AND SHROUD EXPANSIONS
- PREDICTS TRENDS IN MEAN VALUES FOR
  - RECIRCULATION ZONE OF SWIRLING FLOW
  - CONFINED SWIRLER WITHOUT OUTER EXPANSION
- REQUIRES DIFFERENT MODIFICATIONS FOR CONVEX AND CONCAVE WALL SHEAR LAYERS

63-0205-29 A

ALGEBRAIC STRESS MODEL: REYNOLDS-STRESS PREDICTIONS

- GIVES GOOD CORRELATION FOR
  - SIMPLE FLOWS
  - NORMAL STRESSES IN NONSWIRLING RECIRCULATING FLOWS
- GIVES REASONABLE CORRELATION FOR
  - SHEAR STRESSES IN NONSWIRLING RECIRCULATING FLOWS
  - NORMAL STRESSES IN SWIRLING FLOWS
- PREDICTS TRENDS IN
  - SHEAR STRESSES IN SWIRLING FLOWS
- DIFFERENT MODIFICATIONS REQUIRED FOR CONVEX AND CONCAVE WALL SHEAR LAYERS
- MEAN FLOW FIELD PREDICTIONS ARE SIMILAR TO K-ε RESULTS

G3-0205-30 A

SCALAR TRANSPORT MODELS

- K-ε MODEL WITH PRANDTL/SCHMIDT NUMBER — GOOD WHERE GRADIENT DIFFUSION APPROXIMATION IS VALID

- ALGEBRAIC SCALAR TRANSPORT MODEL
  - PROMISING APPROACH
  - MORE VALIDATION WORK IS NEEDED

63-0205-31A

GARRETT

TURBULENCE/CHEMISTRY INTERACTION

- BOTH TWO-STEP AND FOUR-STEP SHOW PROMISE
- MODIFIED EDDY BREAKUP SHOULD CONTINUE TO DEVELOP BECAUSE IT CAN BE EASILY EXTENDED TO MULTISTEP SCHEMES
- BILGER'S TWO-REACTION ZONE MODEL GIVES GOOD RESULTS FOR JET FLAMES, REQUIRES MORE WORK

63-0205-32

DILUTION JET MIXING

- SLIGHTLY UNDERPREDICTS JET PENETRATION AT LOW TO MODERATE J VALUES
- CENTERLINE TEMPERATURES PREDICTED WELL
- TRANSVERSE MIXING PREDICTIONS SLOWER THAN DATA
- EFFECT OF S/D, H/D, J ON MIXING PREDICTED CORRECTLY
- GOOD COMPARISON WITH DATA FOR JET INJECTION FROM
  - ONE WALL
  - BOTH WALLS — INLINE ORIFICES
  - BOTH WALLS — STAGGERED ORIFICES

G3-02‿1-3A

CASES WERE DIVIDED INTO FOUR FLOW CATEGORIES

THE MAIN OBJECTIVE OF THE NASA-SPONSORED AEROTHERMAL MODELING PROGRAM, PHASE I WAS TO ASSESS CURRENT AEROTHERMAL SUBMODELS USED IN THE GARRETT TURBINE ENGINE COMPANY (GTEC) ANALYTICAL COMBUSTOR MODELS.

A NUMBER OF "BENCHMARK" QUALITY TEST CASES WERE SELECTED AFTER AN EXTENSIVE LITERATURE SURVEY. THE SELECTED TEST CASES, BOTH NONREACTING AND REACTING FLOWS, WERE BROADLY DIVIDED INTO THE FOLLOWING CATEGORIES:

- SIMPLE FLOWS
- COMPLEX NONSWIRLING FLOWS
- SWIRLING FLOWS
- DILUTION JET MIXING IN CONFINED CROSSFLOWS

63-0205-34

GARRETT

TURBULENCE AND CHEMISTRY MODELS WERE ASSESSED

THESE TEST CASES WERE USED TO ASSESS THE FOLLOWING SUBMODELS SEPARATELY AND JOINTLY FOR VARIOUS COMBUSTION PROCESSES:

- k-ε MODEL OF TURBULENCE AND ALGEBRAIC STRESS MODEL, WITH AND WITHOUT VARIOUS CORRECTIONS INCLUDING LOW REYNOLDS NUMBER AND RICHARDSON NUMBER CORRECTIONS
- SCALAR TRANSPORT MODELS
- MULTISTEP KINETIC SCHEMES
- TURBULENCE/CHEMISTRY INTERACTION
- SPRAY COMBUSTION

63-0235-36

ADVANCED NUMERICAL SCHEME IS REQUIRED

THE FOLLOWING GENERAL CONCLUSIONS WERE DERIVED FROM PHASE I WORK

- AN ACCURATE NUMERICAL SCHEME SHOULD BE DEVELOPED TO MINIMIZE NUMERICAL DIFFUSION IN THE COMPUTATIONS OF RECIRCULATING FLOWS

- BENCHMARK QUALITY DATA SHOULD BE GENERATED UNDER WELL-DEFINED ENVIRONMENTS FOR VALIDATING THE VARIOUS SUBMODELS USED IN GAS TURBINE COMBUSTION ANALYSIS

63-0205-36

MORE MODEL DEVELOPMENT IS NEEDED

- ALTHOUGH CURRENT AEROTHERMAL MODELS MAKE REASONABLE PREDICTIONS, INTENSIVE MODEL DEVELOPMENT AND VALIDATION EFFORT SHOULD CONTINUE FOR THE FOLLOWING SUBMODELS:
  - ALGEBRAIC STRESS MODEL
  - ALGEBRAIC SCALAR TRANSPORT MODEL
  - TWO-STEP AND FOUR-STEP SCHEMES
  - PROBABILITY DENSITY FUNCTION APPROACH FOR A TWO-STEP SCHEME
  - DOUBLE-REACTION ZONE MODEL

83-0205-37